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HIGH DURABILITY MISSILE DOMES.

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Research Division
Waltham, MA 02154

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Small hemispherical domes were fabricated from discs of polycrystalline ($MgO \cdot Al_2O_3$) and single crystal ($MgO \cdot 3.5\ Al_2O_3$) spinel by hot forging. Applied stresses of 70-105 MN/m^2 at $\sim$1775° C produced deformations of up to 1 cm in $\sim$ 4 hrs. After polishing, the forged domes exhibited generally excellent quality. Some localized regions of optical scatter in the single crystal forgings have been identified as containing alumina precipitates. The present results demonstrate successfully the feasibility of fabricating full-size IR domes by hot forging. This will be the object of future work.

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FOREWORD

This report was prepared by Raytheon Company, Research Division Waltham, Mass., under Contract No. N00014-76-C-0635, entitled, "High Durability Missile Domes." This work is administered under the direction of the Office of Naval Research, Material Sciences Division, Arlington, Virginia. Dr. Arthur M. Diness is the project scientist.

The work was carried out at Raytheon Research Division, Advanced Materials Department. Dr. J. Pappis is the department manager. Dr. Richard Gentilman is the principal investigator. Experimental work was performed by Mr. Edward Maguire.

This is the Interim Technical Report for Contract N00014-76-C-0635. covers the period 1 October 1977 to 30 September 1978. The report was given the Raytheon internal number S-2439.

TABLE OF CONTENTS

Sec.		Page
1.0	INTRODUCTION	1
2.0	EXPERIMENTAL PROCEDURE	5
3.0	RESULTS AND DISCUSSION	8
4.0	SUMMARY	18
REFERENCES		20

LIST OF ILLUSTRATIONS

No.		Page
1	Schematic of Press Forging Technique	6
2	Furnace Assembly	7
3	Deformation Vs Time at Several Temperatures	11
4	Deformation Vs Time at Several Stress Levels	12
5	Press Forged Domes of Spinel	13
6	Press Forged Domes of Spinel	14
7	Press Forged Domes of Spinel	15
8	400X SEM Photos of Polished Dome	16
9	2000X SEM Photos of Polished Dome	17
10	Phase Diagram for the System $MgO \cdot Al_2O_3$	19

1.0 INTRODUCTION

Heat seeking missiles designed for air-to-air engagements face severe operational hazards that either reduce their effectiveness or raise the overall system's cost. The missiles are carried unprotected in exposed positions on aircraft. The infrared transparent dome can be broken during routine handling, pitted by sand and debris during takeoff and landing, or eroded by water droplet impact in flight through rain squalls. These problems are becoming increasingly severe as airspeeds are increased and as the introduction of terrain avoidance radar allows supersonic flight at very low altitudes.

Impact damage that leaves the dome intact but roughens the originally polished outer surface will degrade seeker performance in two ways. First, the minimum resolvable target size will be increased. In the current operational air-to-air missile, this factor is not critical. However, in the designs under consideration for the next generation missiles, seeker resolution will be severely affected by dome erosion. Second, roughening of the dome increases the amount of sunlight scattered into the seeker optics, raising the noise level in the infrared detection system and thus limiting the ability to detect targets. While these effects have not been well characterized, it is of considerable concern in current development of seekers designed for head-on approach.

Finally, immediately after missile launch, high tensile stresses are generated in the dome due to transient nonuniform aerodynamic heating of the dome. The severity of these stresses depends on the nature of the dome material (its thermal conductivity, heat capacity, and thermal expansion coefficient) and on the specific aerodynamic flight regime. For a next generation missile launch at Mach 1.5 with a powered flight lasting 2.0 sec, significant tensile stresses develop at the inside dome surface during the missile's acceleration, reaching a maximum of approximately 12,000 psi just after the

end of the powered flight. However, the fracture strength of magnesium fluoride is only 10,000 psi at 450° C, the approximate average temperature of the dome during flight at the time of the maximum thermally induced stress.

Early forms of infrared missiles operated at short infrared wavelengths where fused silica domes could be used. This material has a very high resistance to thermal shock but suffers from rain erosion. Magnesium fluoride domes have provided higher strength, adequate resistance to rain erosion (for current applications), transparency in the 3 to 5 μm atmospheric window, and the ability to withstand the thermal shock of current missiles in subsonic launch. However, magnesium fluoride domes are predicted to fail in either supersonic launch of current missiles or subsonic launch of the next generation designs and also to be adversely affected by rain during supersonic captive carry.

The need for a new, more durable missile dome is clear. New missile designs are being compromised by the lack of a dome material with the required strength, hardness, and thermal conductivity that can be produced at an acceptable cost. However, there are several highly durable crystalline oxide materials (Table 1) that are transparent at ultraviolet, visible, and infrared wavelengths out to 5 μm that will serve the optical needs of future seeker designs. Specifically, spinel has become a leading candidate material for future air-to-air missile domes.

The particular dome shape of interest during this investigation is a hemispherical sheel approximately 70 mm diameter and 3 mm thick. One approach proposed for the fabrication of such a shape from refractory oxides is to press forge flat plates at high temperatures. Work reported in the literature by Heuer, Hwang and Mitchell[1,2] and by Becher[3] showed that single crystals of spinel could be deformed plastically in compression. The experiments reported here were attempted to see if this plastic deformation

TABLE 1

INFRARED TRANSMITTING MATERIALS RANKED ACCORDING TO THERMAL SHOCK RESISTANCE AT 450° C

Material	Absorption Between 4-5 μ in 2 mm T = 450° C	Resistance to Thermal Stress ($\sigma K/\alpha E$) RT	450° C	R. T. Fracture Strength (psi)	Knoop Hardness	Crystal Structure
Si	40%	296	60	9,000	1150	Cubic
Ge	60%	88	25	13,500	690	Cubic
Al_2O_3	8%	47	21	50,000	2200	Hexagonal
$MgAl_2O_4$	3%	22	11	28,000	1700	Cubic
MgO	<1%	29	8	23,000	900	Cubic
Y_2O_3	<1%	25	7	28,000	800	Cubic
ZnS	Transparent	26	6	15,000	356	Cubic
CdS	Transparent	19	6	8,000	130	Hexagonal
ZnSe	Transparent	23	5.5	7,500	150	Cubic
MgF_2	<1%	19.4	3.2	22,000	576	Tetragonal

process could be utilized where the stress applied was not simple compression. Also, it was desired to determine the feasibility of using polycrystalline as well as single-crystal spinel.

Spinel of excellent optical quality is available in both single-crystal and polycrystalline form. The selections made were single-crystal boules of alumina-rich spinel, generally 1 MgO to 3.5 Al_2O_3, grown by a Verneuil technique* and plates of polycrystalline spinel of 1:2 :: $MgO:Al_2O_3$ stoichiometry produced by a fusion casting process.[4] The alumina-rich material has a lower yield stress than the stoichiometric 1:1 composition. As a preliminary step toward full-sized IR domes, experiments were size limited by the diameter of available single crystals of spinel, slightly over 3.2 cm. But the validity of the concept could be demonstrated by forging domes of smaller diameter but comparable curvature.

The present hot forging work was begun in 1977, with studies of simple beam deformation of alumina-rich spinel in three-point bending. During 1978, the technical feasibility of forging flat discs into hemispherical shells was demonstrated successfully.

---

*Adolf Meller Co., Providence, RI.

2.0 EXPERIMENTAL PROCEDURE

Figure 1 shows schematically the press forging technique employed to form hemispherical dome shapes from flat plates of spinel. The plates, 2.62 - 2.86 cm diameter and 0.19 cm thick, were set into a hemispherical cavity in a graphite die and loaded at their center points by a matching hemispherical graphite punch. The radius of curvature was approximately 1.2 cm. Spacers of Grafoil 0.04 cm thick, between the spinel plate and the graphite die faces reduced interactions to a minimum.

Loaded in this manner, with the edge simply supported and the force applied at the center, the maximum stress developed is determined by[5]

$$\sigma = \frac{3(1+\mu)P}{2\pi t^2}\left(\frac{1}{\mu+1} + \log_e \frac{r}{r_o} - \frac{1-\mu}{1+\mu}\,\frac{r_o^2}{4r^2}\right)$$

where σ = maximum stress

μ = Poisson's ratio

P = central load

t = thickness of plate

r = radius of plate

r_o = radius of central loaded area

As the plate deforms, the radius of the central loaded area increases. This was taken into account and the load increased when necessary to maintain any given stress level. The loads that were applied produced maximum stresses in the plates of 525-1050 kg/cm^2 (7.5-15 ksi).

In Figure 2 the furnace assembly is shown with the graphite die in place. The load was applied to the top punch by weights suspended below the furnace. This loading was static with incremental changes to maintain a given stress level as deformation proceeded. The extent of deformation

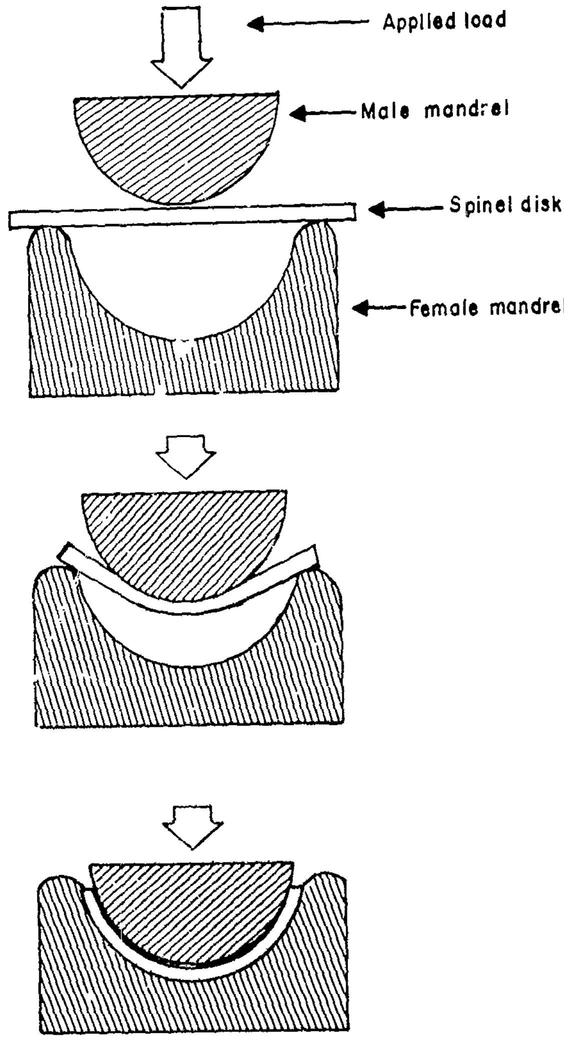


Figure 1. Schematic Diagram in Cross-Section of Hot Forging a Spinel Disc into a Hemispherical Dome Shape

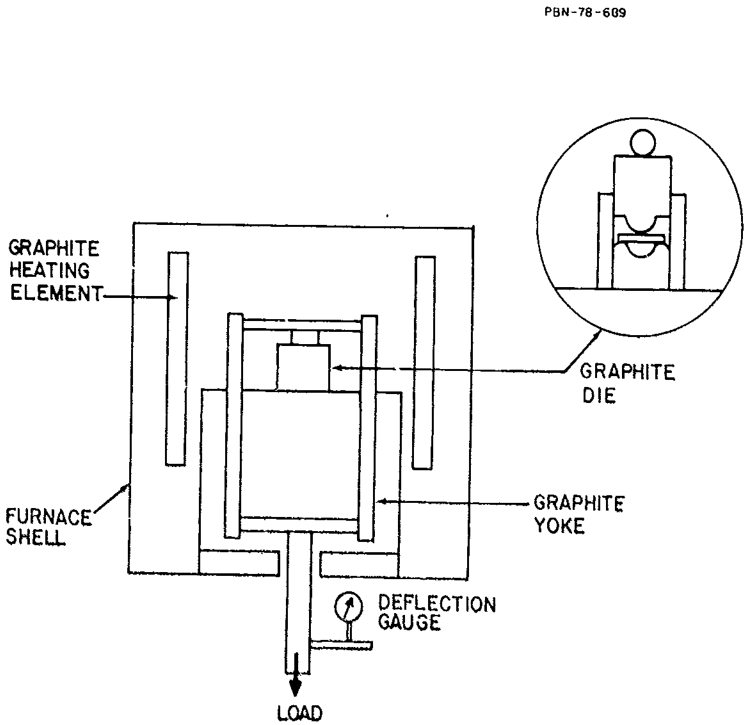


Figure 2. Furnace Assembly.

was monitored on a dial indicator. A graphite heating element provided temperatures of 1750° -1800° C in an atmosphere of helium.

3.0 RESULTS AND DISCUSSION

In the course of the experiments reported here, twenty-six (26) runs were made with single-crystal spinel and seven (7) runs with polycrystalline plates. A summary of these forging runs is presented in Table 2. Data were selected from these to illustrate the effects of temperature and pressure on deformation rates. In Figure 3, deformation is seen to take place more rapidly as temperature is increased. These spinel plates were subjected to a stress of 875 kg/cm^2 (12.5 ksi). Some deformation is shown at zero time because the load was applied throughout the heatup portion of the cycle while time was measured from the point at which a given temperature level was reached. Data for polycrystalline plates indicates lower rates under comparable temperature and pressure conditions. Pressure was the variable in Figure 4. As expected, the deformation was accelerated by increasing pressure. Good results were obtained at temperatures of 1750° to 1780° C and pressures of 700-1050 kg/cm^2 (10-15 ksi).

A number of the domes produced are shown in Figures 5, 6, and 7. There was no difficulty with gross defects such as cracks or tears. Surfaces did suffer some degradation as a result of contact with graphite. However, the surfaces were easily restored by polishing and as the polished domes in these photos demonstrate, the optical quality was excellent.

Some domes appeared to have cloudy areas that were not removed by surface polishing. Under the optical microscope, these areas were seen to contain numerous small crystals. Figure 8 shows SEM photos at 400X magnification of a clear area and a cloudy area of typical domes. The latter area is examined more closely in Figure 9 at 2000X. An x-ray microprobe was used to analyze the spots marked by the white dots in the lower photo. The

TABLE 2

SUMMARY OF SPINEL HOT FORGING RUNS

Run No.	Sample Diam. cm	Sample Thickness cm	Temp. °C	Max. Stress Kg/cm^2	Time hr	Deformation cm	Loss %	Comments
20	2.78	0.19	1750	1120	5.5	0.32	6.2	cracked
21	2.78	0.09	1775	1050	8.0	0.68	---	cracked
22	2.78	0.25	1850	700	6.0	1.40	---	broken
23	2.78	0.19	1800	1050	2.5	1.20	---	broken
24	2.78	0.19	1800	700	----	----	---	broken
25	2.78	0.19	1775	1050	8.0	0.38	12.3	OK
26	2.78	0.20	1750	1260	12.0	0.71	23.8	broken
27	2.78	0.20	1750	980	12.0	0.46	34.3	OK
28	2.78	0.21	1780	1050	4.5	1.09	---	broken
29	2.78	0.19	1760	1050	6.0	0.42	9.2	OK
30	2.78	0.19	1750	1050	12.5	0.41	22.5	OK
31	2.78	0.20	1800	1050	8.0	0.45	44.2	OK
32	2.78	0.19	1780	840	7.5	0.53	31.9	OK
33	1.90	0.19	1775	1050	4.0	0.50	11.3	OK
34	1.90	0.20	1785	1050	7.0	0.50	5.0	OK
35	2.60	0.19	1775	1050	11.0	0.59	3.5	OK
36	2.60	0.18	1770	1050	31.5	0.72	2.4	OK
37	2.60	0.19	1760	1050	6.0	0.94	3.8	OK
38	2.60	0.19	1765	1050	5.8	0.90	2.0	OK
39	2.60	0.19	1775	1050	6.2	0.91	1.3	OK
42	2.85	0.20	----	1050	----	----	---	broken, polyxtal
43	2.85	0.20	1780	875	8.0	1.09	4.7	OK, polyxtal
44	2.60	0.20	1770	875	6.0	0.77	2.5	OK
45	2.60	0.21	1800	875	2.5	0.84	6.1	OK
46	2.60	0.20	1780	875	5.0	0.93	5.7	OK
47	2.60	0.19	1780	875	3.5	0.90	9.1	OK

TABLE 2 (Cont'd)

Run No.	Sample Diam. cm	Sample Thickness cm	Temp °C	Max. Stress Kg/cm^2	Time hr	Deformation cm	Loss %	Comments
48	2.53	0.20	1790	875	8.0	0.82	4.8	polyxtal some cracks
49	2.53	0.20	1720	875	---	----	---	polyxtal broken
50	2.53	0.20	1775	700	8.5	0.79	3.8	polyxtal OK
51	2.53	0.18	1750	700	8.5	0.70	4.3	polyxtal OK
52	2.53	0.19	1775	700	11.5	0.72	3.8	polyxtal OK
53	2.60	0.20	1785	1050	5.5	0.37	---	OK
54	2.60	0.19	1785	1050	3.8	0.89	2.9	OK

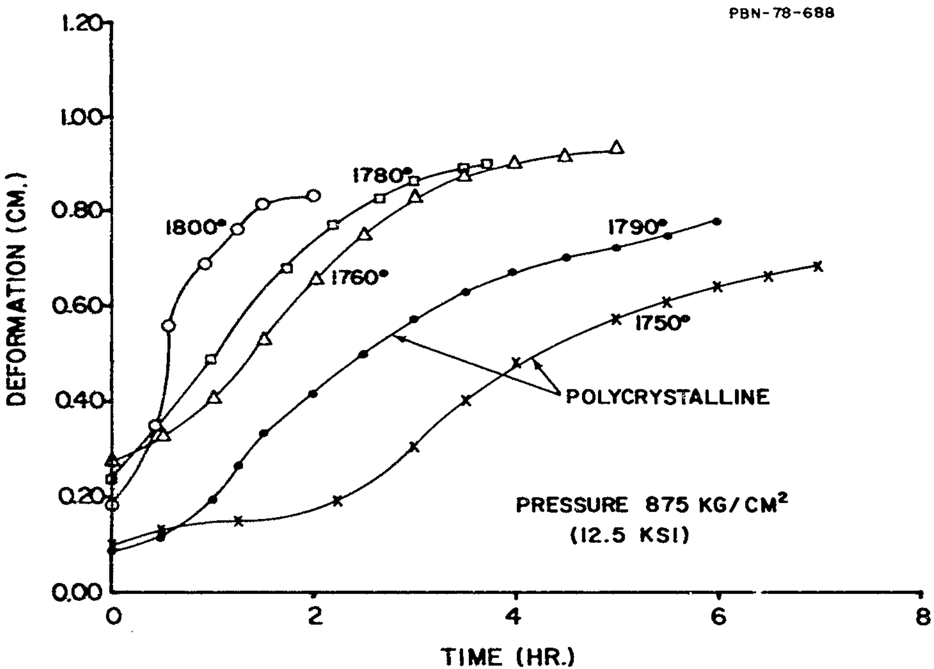


Figure 3. Deformation Vs Time at Several Temperatures.

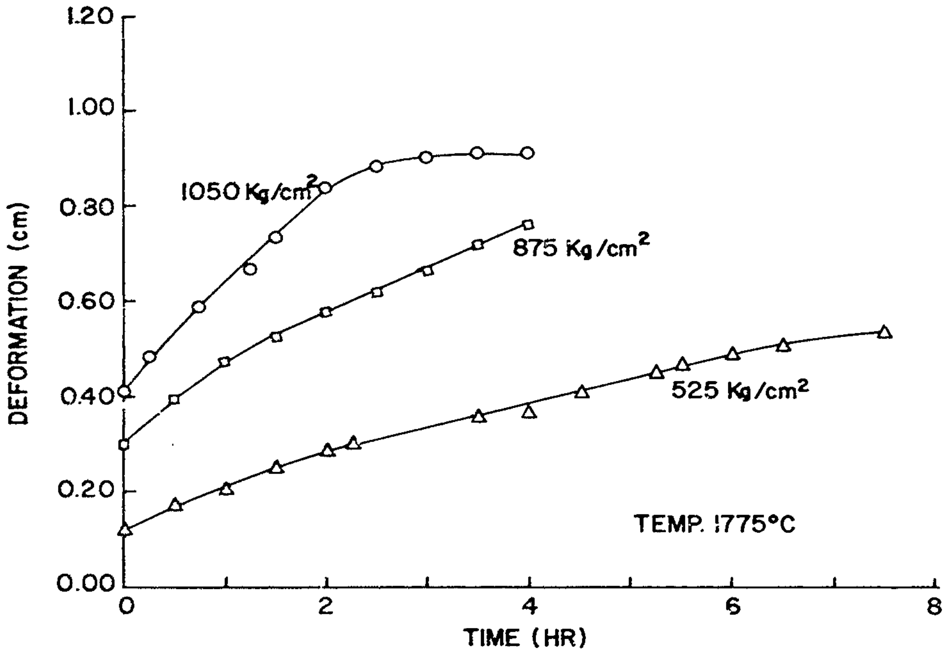


Figure 4. Deformation Vs Time at Several Stress Levels.

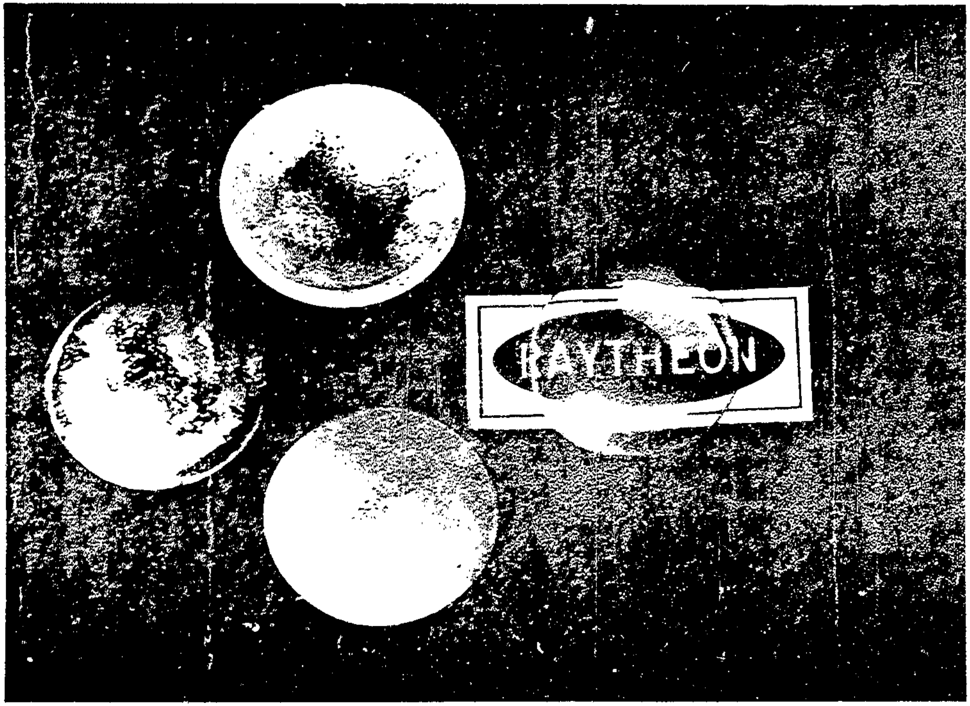


Figure 5. Press Forged Domes of Spinel.

Figure 6. Press Forged Domes of Spinel.

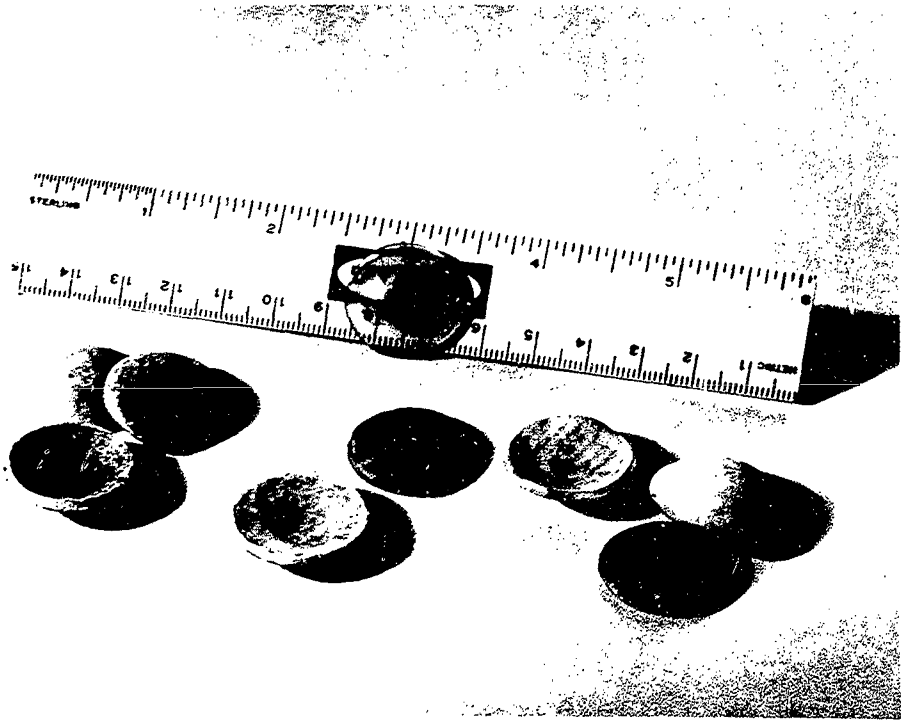
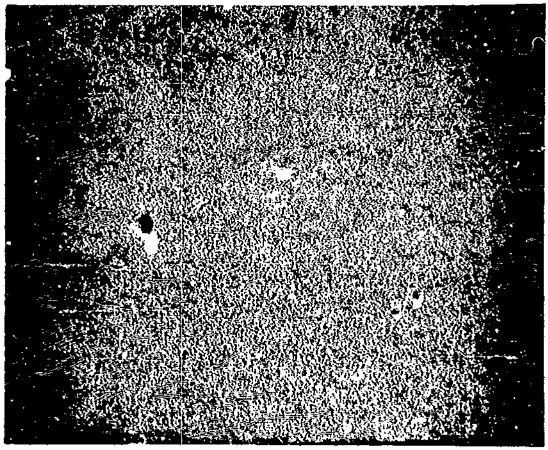
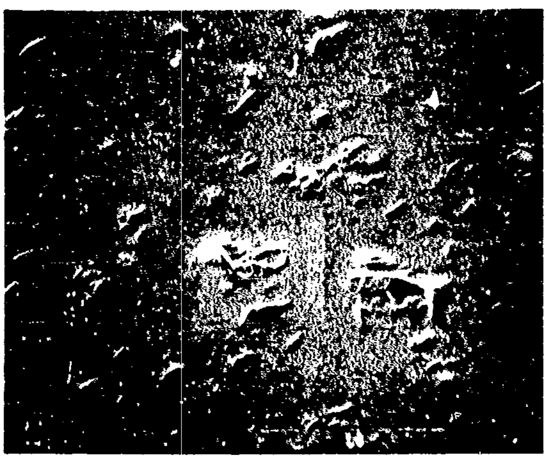


Figure 7. Press Forged Domes of Spinel.



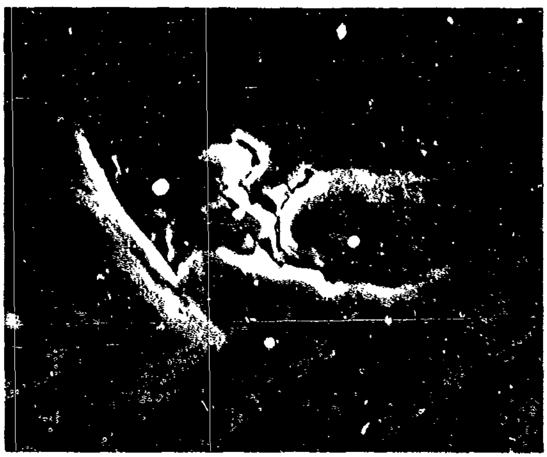
400 X SEM CLEAR AREA



400 X SEM CLOUDY AREA

Figure 8. 400X SEM Photos of Polished Dome.

2000 X SEM



2000 X SEM WITH MARKERS

Figure 9. 2000X SEM Photos of Polished Dome.

three individual grains were identified as Al_2O_3 while the background matrix was spinel. It appears that some precipitation/ recrystallization of alumina had occurred. This behavior was seen in domes press forged from plates of single-crystal spinel but not polycrystalline ones. A check of the phase equilibria of the system (Figure 10) provides an explanation for the difference in behavior. In the case of 3. 5 to 1 single-crystal material, the forging temperatures of 1750° -1800° C placed the piece in a region where two phases, spinel and alumina, can exist. Under the same conditions, 2 to 1 polycrystalline material is within the single-phase spinel area.

4.0 SUMMARY

The concept of press forging hemispherical dome shapes from flat plates of magnesium aluminate spinel has been demonstrated. Small domes, 2. 54 cm in diameter and 0. 76 cm high, were fabricated from both single-crystal and polycrystalline material. Excellent optical quality was maintained. The only potential problem was presented by precipitation/ recrystallization of Al_2O_3 in single-crystal 3. 5:1 spinel. This work is being pursued toward the fabrication of larger-sizes domes.

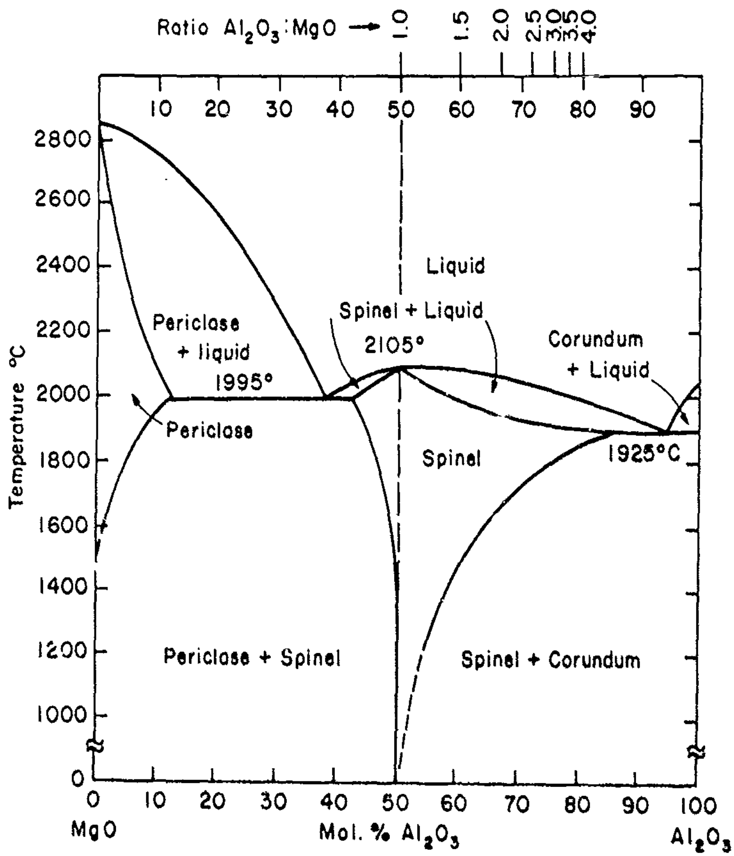


Figure 10. Phase Diagram for the System MgO-Al_2O_3.

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